557197

"X-33 Tank Failure During Autoclave Fabrication"

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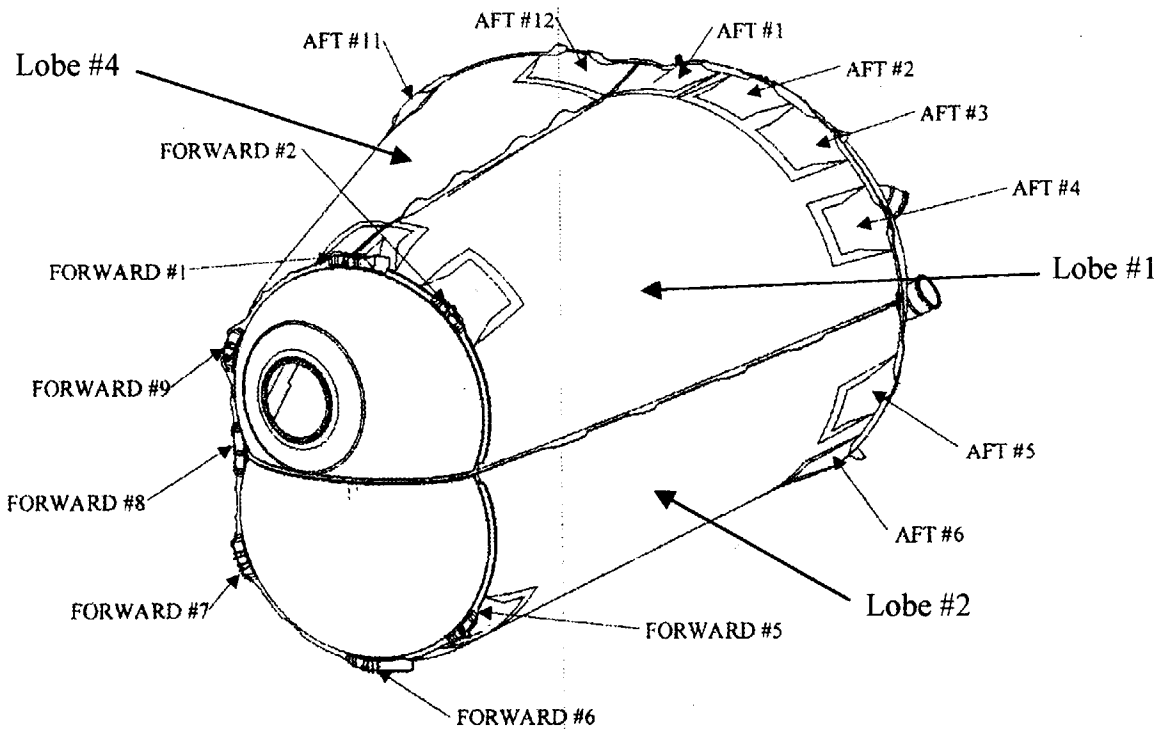
History

The Composite Liquid Hydrogen Tank (Tank # 1 of 2) for the X-33 Flight Vehicle is Made Up of 4 Lobes that are Sandwich Construction, Bonded to a Frame of Longerons

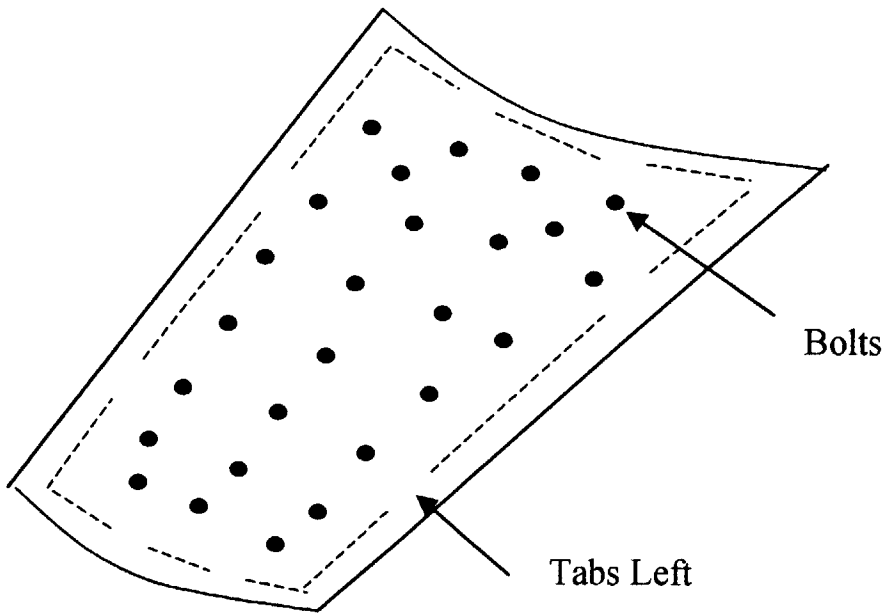


Lobes #1 and #4 Showed Local Disbonds to the Longerons they were bonded to. The "Bad" areas were cut away and patched with new material. The new material was cured by placing the entire tank in a heated autoclave with no pressure. (Dec. 23, 1998)

History

Upon removal from the Autoclave, it was noted that Lobe #1 had severe skin/Core disbonds on the inner and outer skins. The Skins on this lobe were cracked as well. The core was disbonded from the inner skin across the entire acreage, except for spots around the lobe perimeter. The Outer skin was seperated from the core in a region near the center of the Lobe.

Lobe #1 was removed from the Tank on January 13, 1999. Bolts were place through the lobe to hold it together and the cuts on the inner skin were not continuous, but "tabs" were left for final cutting and removal.



History

Lobe #1 had to be forced into place with rather high loads.

As the first 3 tabs were cut, loud "bangs" were heard and the lobe buckled. This indicated high residual stresses.

The Lobe was Removed from the Tank and the Inner facesheet was removed from the lobe.

At this point, the inner facesheet to core bond had seen 7 excursions up to 350F for a total time of 9 hours at 350F.

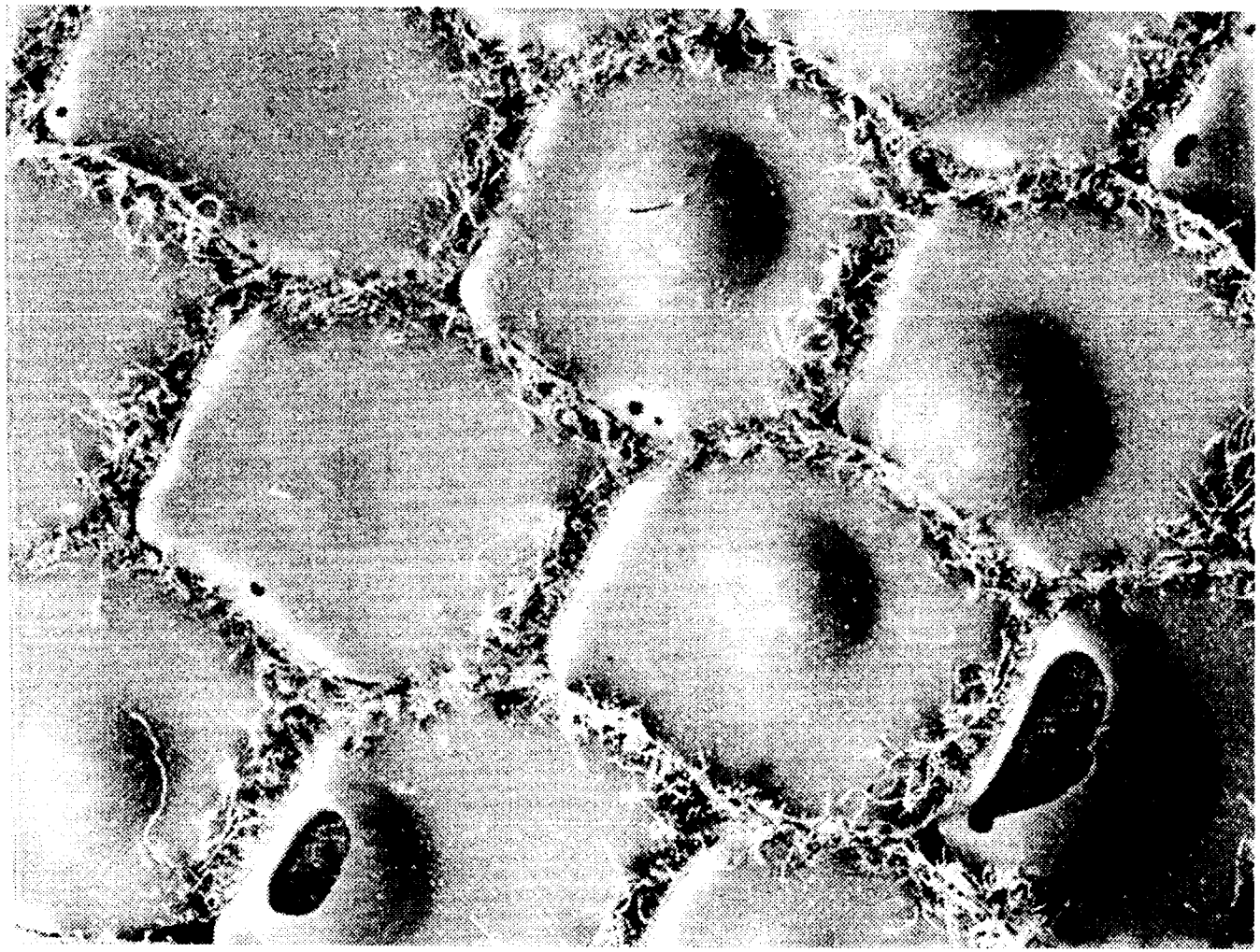
The Temperature of the autoclave on the final cycle got up to 387F for 6 minutes.

The out-time of the adhesive on Lobe #1 was 6 days. (Lobe #4 was 9 days).

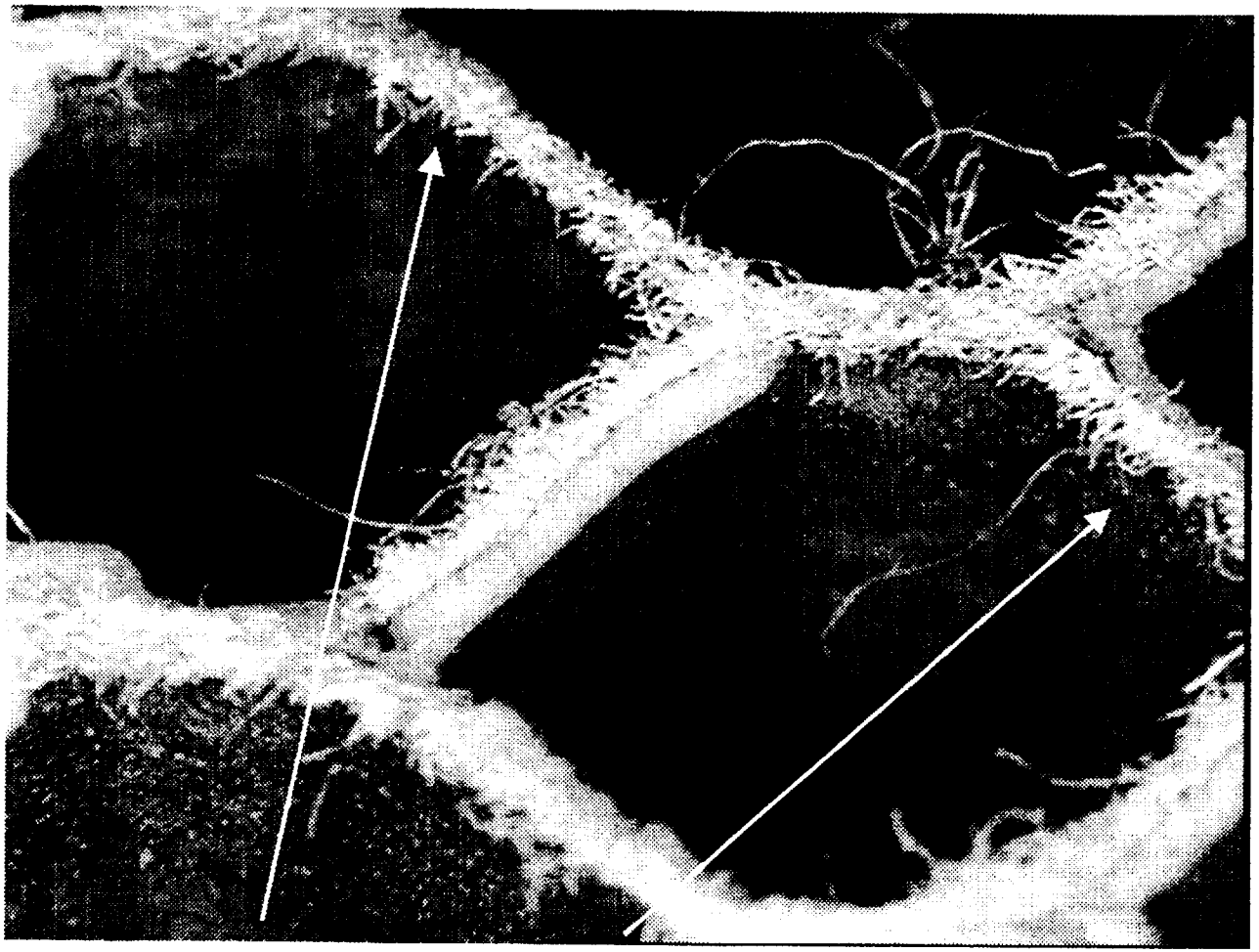
Lobe #4 showed no anomalies. This lobe was most similar to lobe #1.

Examination

Upon closer inspection of the disbonded facesheet, it was noted that there was a lack of filleting into the honeycomb core. Good fillets are critical to bond strength.



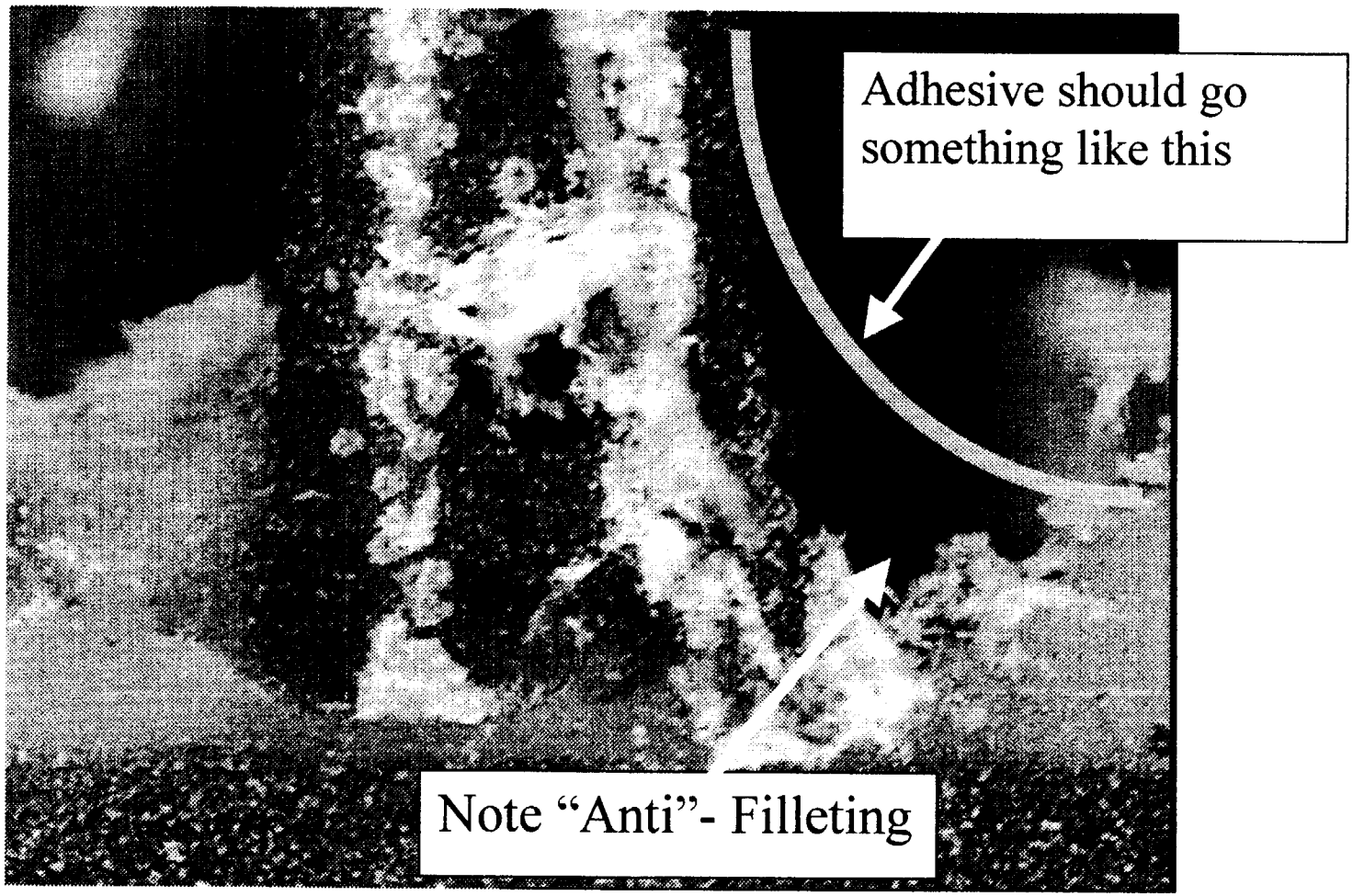
Examination



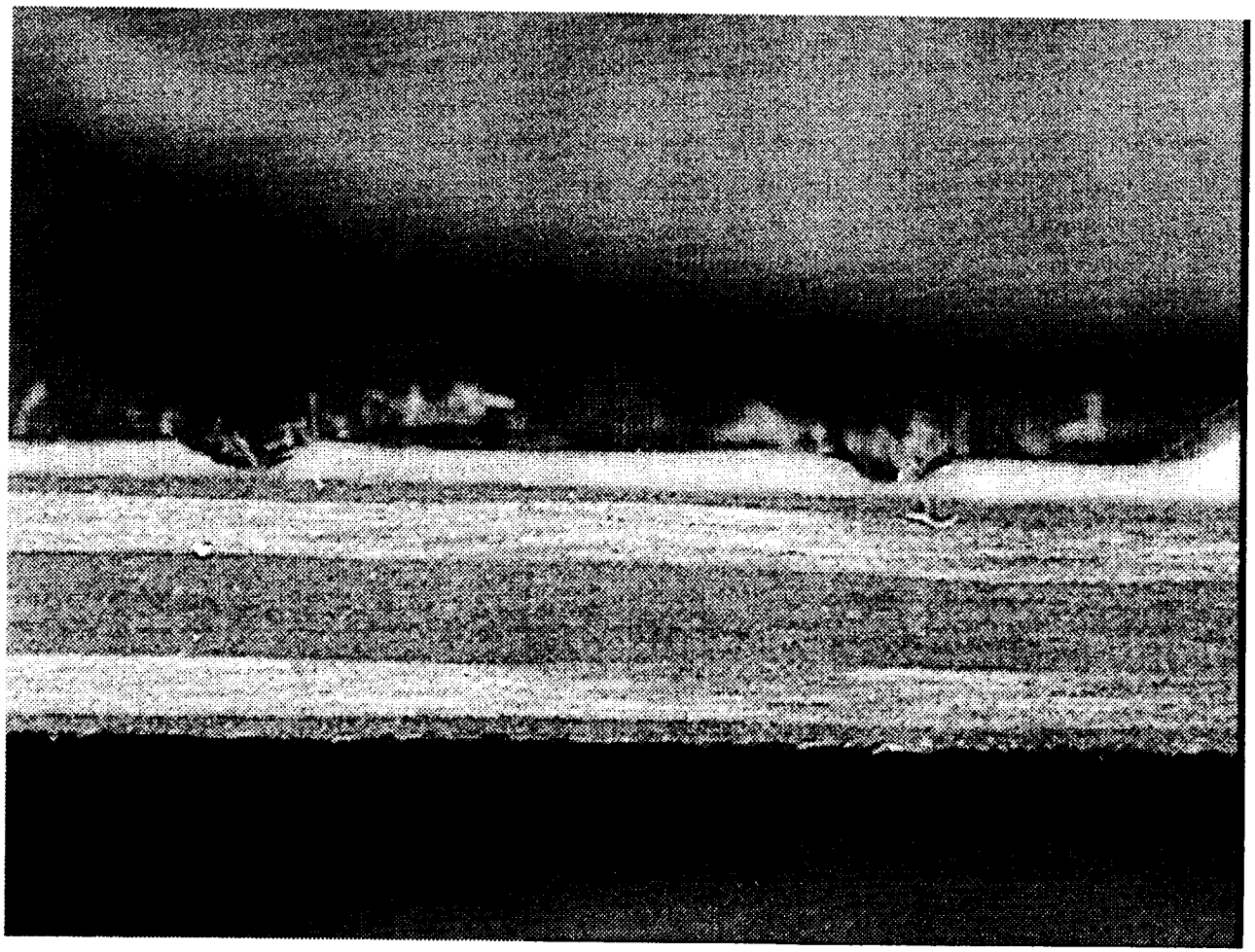
Note Lack of Fillets into Cells

Examination

Specimens were cut from lobe #1 and examined more closely:



Examination

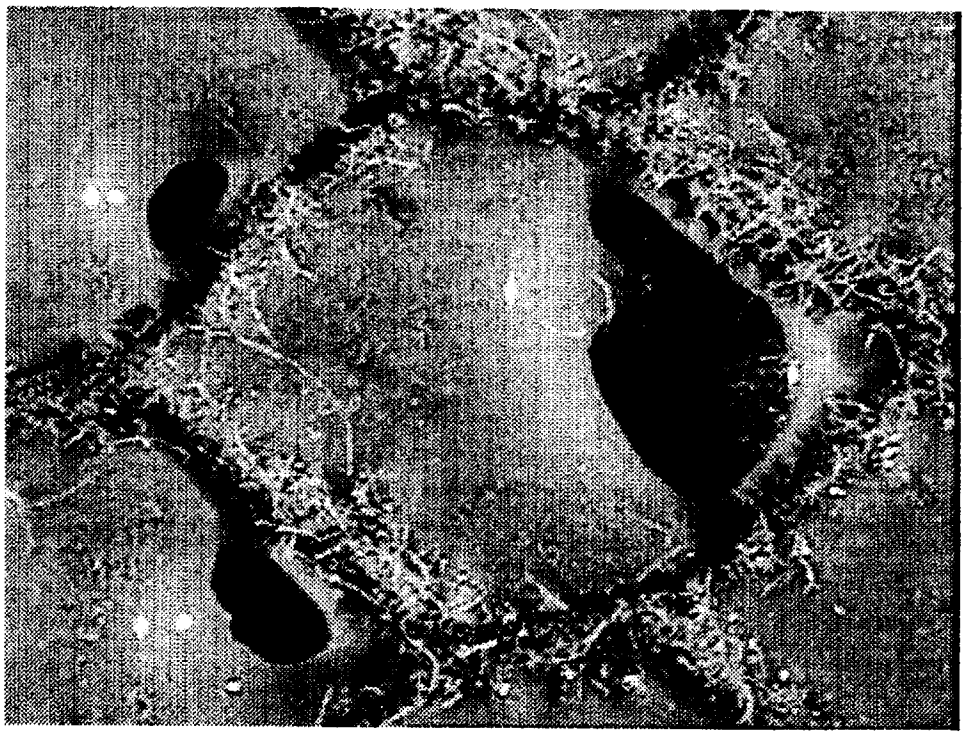


Testing

Chemical Testing was performed to look for contaminants that may have weakened bondline:

ESCA, FTIR, GCMS and EDS Analyses all showed no contamination.

Further microscopy revealed that, for the most part, the adhesive only bonded to the "fuzz" on the surface of the honeycomb.



Testing

A series of tests were performed to determine the effect of multiple cure cycles on the adhesive. ***Note: These Specimens were made with the adhesive at a one day out time!***

# of Cycles	Test Temp.	# of Specimens	Average Stress	S.D.
1	77 F	5	496 psi	13 psi
1	350 F	5	205 psi	11 psi
6	350 F	4	235 psi	29 psi
12	350 F	5	224 psi	25 psi
6	**390 F**	**5**	**150 psi**	**14 psi**
12	**390 F**	**5**	**127 psi**	**21 psi**

# of cycles is not nearly as important as test temperature

On Cycle in Which the Facesheet Disbonded, the temperature reached 387F

Mechanical Tests on the Laminates (facesheets) showed the composite to be of good structural quality on a macroscopic scale.

Adhesive Out Time and Cure Pressure Testing on Sandwich Flatwise Tensile Strength

	Test#1	Test#2	Test#3	Test#4	Test#5	Test#6
Out Time	1 day	1 day	8 days	8 days	16 days	0.5 days
Cure Pressure	6.0 psi	11.0 psi	12.0 psi	87 psi	6.0 psi	11.0 psi
Strength	663 psi	700 psi	**380 psi**	706 psi	**314 psi**	714 psi

Each Strength Value is the average of 5 tests.

Thus the Out Time of the adhesive is critical to the sandwich Structure's flatwise strength (unless the cure pressure is extremely high)

Removal of Lobe #4

Since Lobe #4 still has disbonds along the longerons, it was decided to remove this lobe and maybe learn some more information regarding the integrity of the lobes.

The first test performed before removing lobe #4 was to try to determine the state of stress within the lobe.

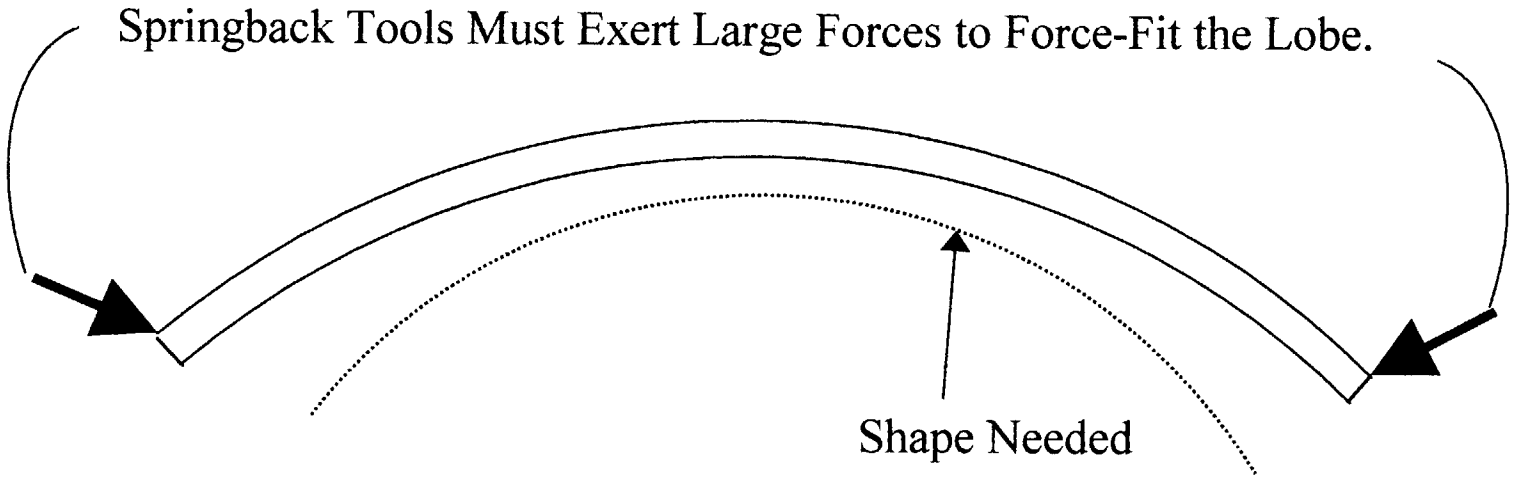
Areas about 6 in. X 6 in. were marked on the outer facesheet and on the inner facesheet. Strain gage rosettes were placed within these areas and zeroed out.

The areas were then cut from the lobe and the strain readings taken as the sections were laying flat.

Removal of Lobe #4

The results showed that the inner facesheet was in a state of bi-axial compression and the outer facesheet was in a state of bi-axial tension.

Not unexpected as the lobes had to be "recurved" to fit the frame since they tend to "flatten-out' due to springback after removal from the autoclave.



As the Temperature rises, this effect is less pronounced…closer to "stress-free" temperature of 350F

Removal of Lobe #4

Another source of residual loads in the lobes are the CTE mismatch of the inner and outer facesheets and the longerons.

Specimen Origin	Direction	CTE (10E-6)
Outer Faceshhet	Axial	1.7
Outer Facesheet	Circumferential	0.9
Inner Facesheet	Axial	2.4
Inner Facesheet	Circumferential	1.4
Longeron	Axial	4.6

Specimens were cut from lobe #4 and tested in Flatwise tension. The Average of 26 specimens was **324 ± 34 PSI**. The high/low values were 372/269 PSI.

Expected values were about 600 PSI…Thus only half of the expected strength was realized.

Failure of Lobe #1

The Failure of Lobe #1 during the non-pressurized autoclave cycle appears to be a result of several factors.

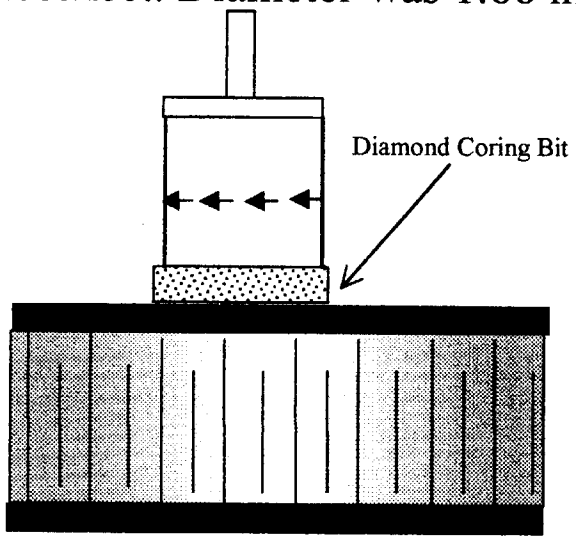
1. A low facesheet to core bond strength
2. Much lower adhesive strength at elevated temperatures
3. High Residual loads in the lobes due to forcing them into place
4. Mismatch in CTE between Inner and Outer facesheets and Longerons
5. Increase in pressure within cells due to elevated temperature
6. No pressure was used in the autoclave. This pressure probably helped "hold together" the tank during the other cure cycles.

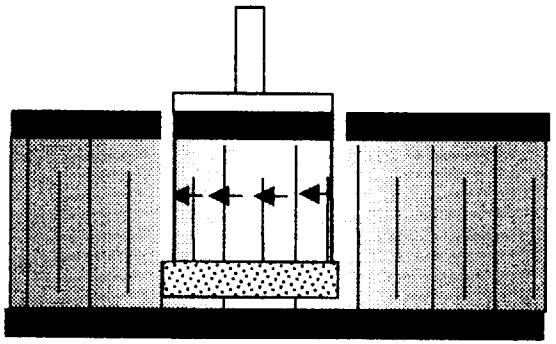
The question now arises as to the structural integrity of the remaining lobes!

It was decided that "Plug Pulls" would be the least intrusive way of checking the bondline strength.

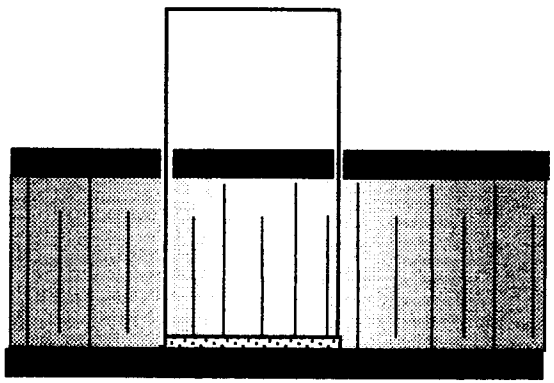
Test Method

Core out the outer facesheet and honeycomb core and stop before damaging the inner facesheet. Diameter was 1.88 inches.



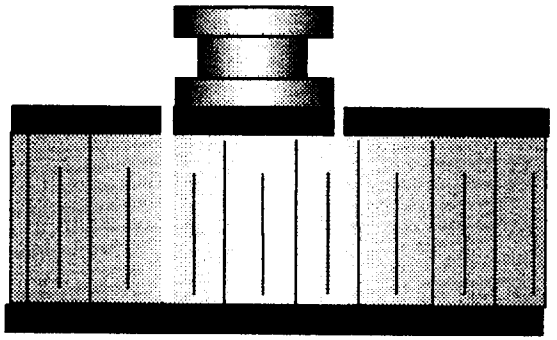


Finish coring to inner facesheet by hand

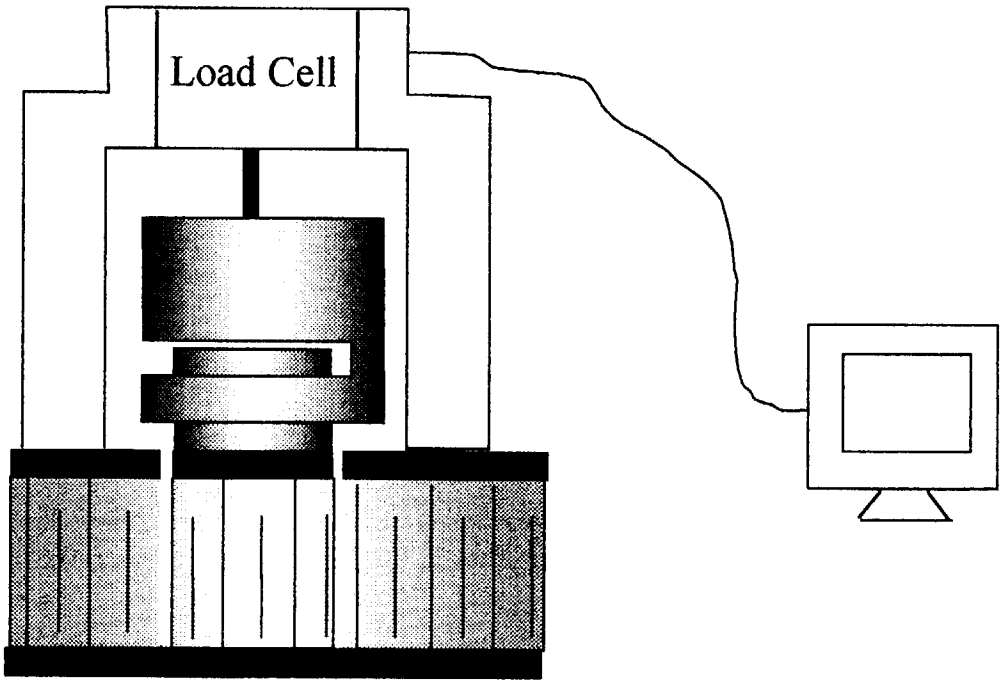


Plug Pulls

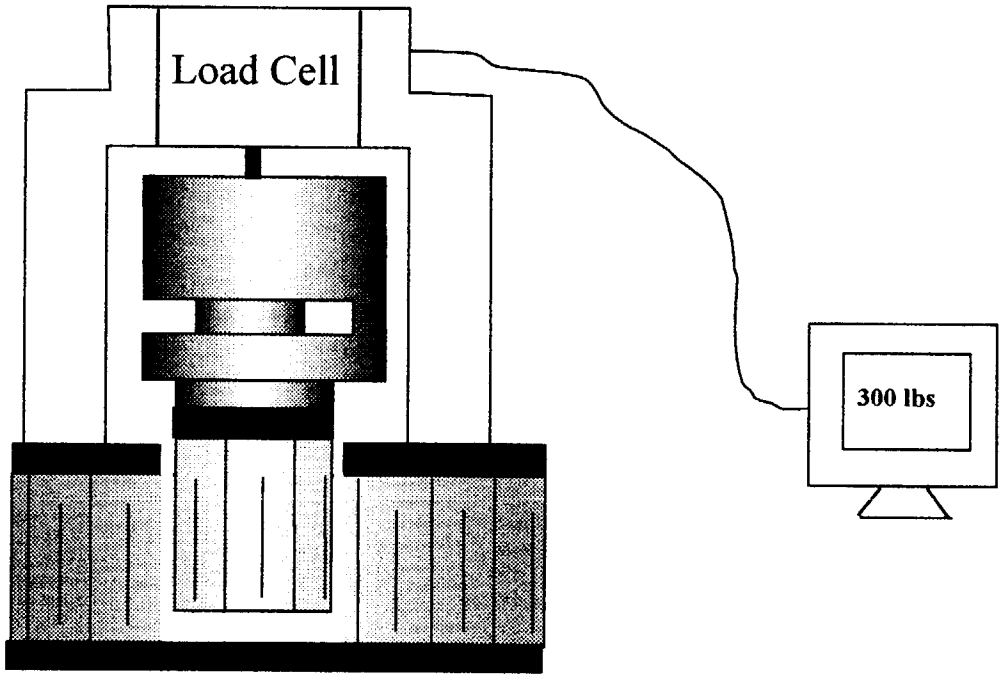
Bond pull buttons to outer facesheet with EA 9394



After cure, attach pull apparatus and see how many pounds it takes break inner facesheet/core bond.

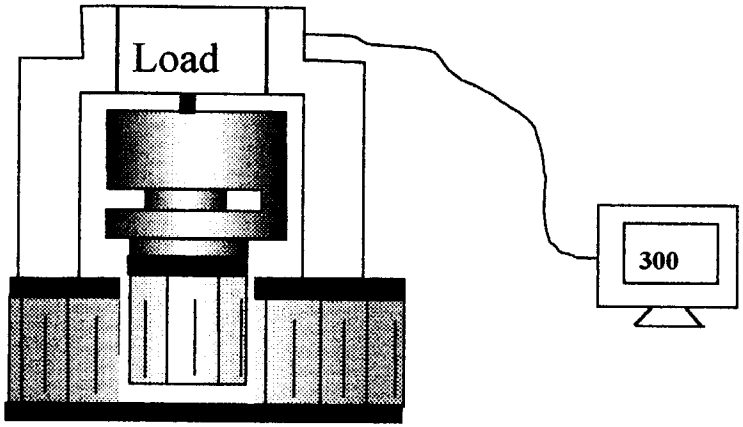


Plug Pulls



Originally 3 pulls on Tank #1 Lobe #2, 1 pull on Tank #1 Lobe #3, and one pull on each of the 4 Lobes of Tank #2 were performed. Six pulls were conducted on removed Lobe #4 of Tank #1.

Plug Pulls



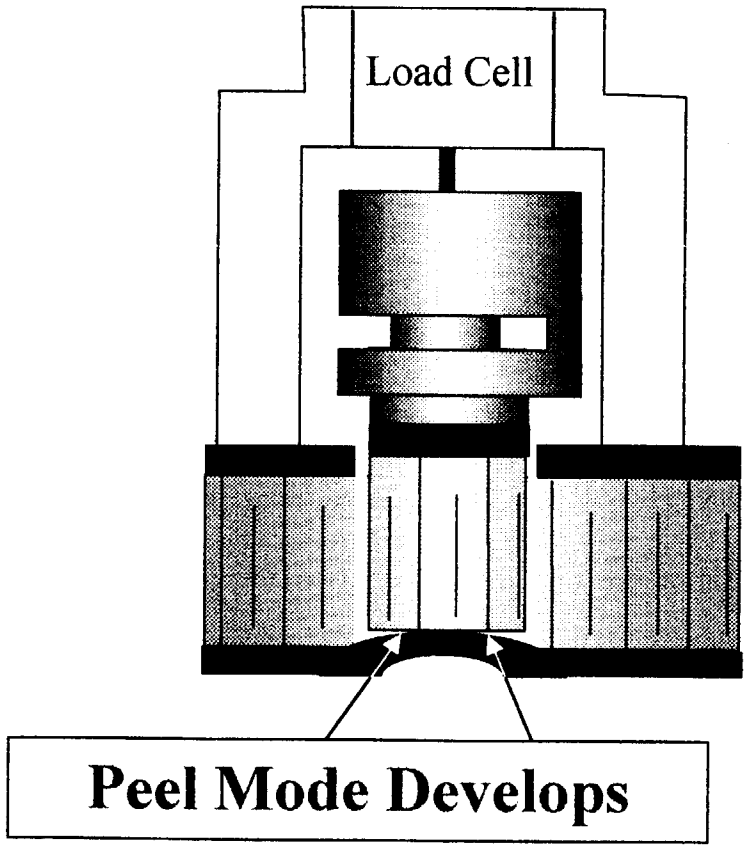
Values from Original Plug Pulls

Plug Pull	# Tested	Stress (PSI)	Failure Mode
Tank #1/Lobe #2	3	153±12	Cohesive, Some Core
Tank #1/Lobe #4	6	115±13	Adhesive
Tank #1/Lobe #3	1	126	50% Adhesive/50% Cohesive
Tank #2/Lobe #1	1	117	Adhesive
Tank #2/Lobe #2	1	138	Adhesive
Tank #2/Lobe #3	1	152	Adhesive
Tank #2/Lobe #4	1	138	80% Adhesive/20% Core

Plug Pulls

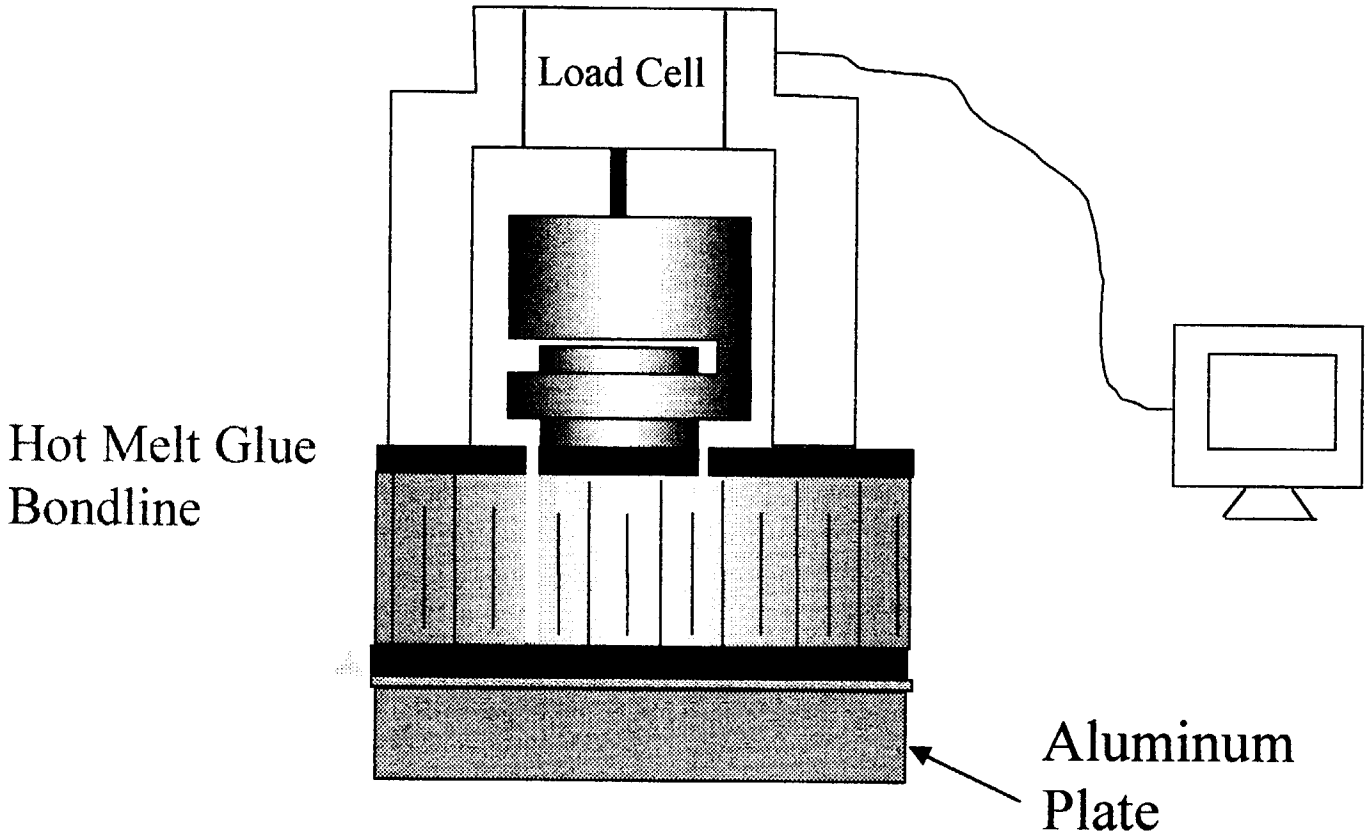
These values were much lower than the 324 PSI value obtained from the 2"x 2" flatwise tensile tests cut out from removed lobe #4.

Problem was subsequently attributed to Plugs going into a "Peel" mode due to inner skin deflection.



Plug Pulls

Solution was to use "Backing Plates" to stiffen inner skin.



These Backing Plates were applied to the inside of the tank at each new plug pull location

Plug Pulls

3 Pulls were done on each of the 4 lobes of the two tanks

All Values in PSI

Tank #1	Test 1	Test 2	Test 3	Average	S.D.	S.D./Avg
Lobe 1	>503	363	459	**442**	72	16
Lobe 2	434	448	331	**404**	67	17
Lobe 3	316	405	382	**368**	46	13
Lobe 4	403	294	405	**367**	63	17
Tank #2						
Lobe 1	329	351	353	**344**	13	4
Lobe 2	413	373	370	**385**	24	6
Lobe 3*	306/331	447/315	254/304	**336/317**	100/14	30/4
Lobe 4	455	392	458	**435**	37	9

*Two sets of tests were performed on Lobe #3 of Tank #2 since the first set of numbers had high scatter?!?!?

Developing FWT "Allowables"

Problems……What Data to Use????????

Once Data is selected, B-Basis, Weibull, Lowest Value, Lowest Value Plus Knockdown……OR

85% of Mean if Greater?????? Than B-Basis???????????

NASA Philosophy: A Bondline failure will propagate in Mode I peel after failure is initiated….the "unbond front" is not self arresting…..thus Weibull will give probabilities based on the ENTIRE ACREAGE of each lobe…NOT on the amount of material tested!!!!!

Developing FWT "Allowables"

Cryopumping will affect entire acreage of all lobes. This pressure was known to be in the range from a few PSI to up to 80 PSI (from test data). Residual stresses will add more (as in the Autoclave Failure).

Using all of the FWT data at –423F, a B-basis allowable comes out to be 66 PSI. LMSW used the minimum value of 141 PSI based on 5 tests.

This represents 20 square inches of bondline area tested. EACH lobe has approximately **64,000 square inches**.

Thus there was a 20/512,000 % chance that the "true" weakest area was tested!!!

Developing FWT "Allowables"

In order to have a Statistically meaningful Weibull analysis, many tests must be performed (usually at least 20). 20 data points existed for RT Testing after 50 cycles of LH2